An Alternative Control Topology for Interferometer Sensing and Control in KAGRA

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Here we briefly discuss the limitations of the current ISC control topology and how an alternative approach might surpass the limitations. Originally, this was proposed for alignment/angular sensing and control (ASC) but is not exclusive for ASC and can be applied for even LSC wherever applicable.

1 Current Control Topology

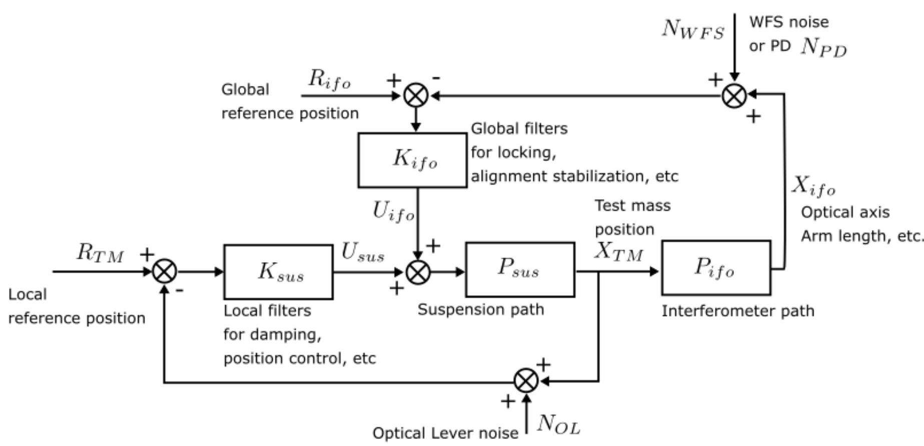

Figure 1: Current interferometer control topology

As shown in Fig. 1, the current interferometer control topology consists of two loops which we usually refer to the local control and the global control loops. For the local control loop, the test mass position X_{TM} is feed back via an optical lever to local suspension control filters K_{sus} which are dedicated for position control and damping, etc. The local control ouputs an actuation signal U_{sus} to the suspension actuators and is converted to the mirror position via the suspension path/transfer fucntion P_{sus}.

As for the global control path, the test mass position is converted to some interferometer degrees of freedom X_{ifo} such as the tilt of the optical axis via the interferometer path P_{ifo}. This is sensed by the wavefront sensors or PDs and then feed back to some global controllers K_{ifo} which are designed for locking or angular sensing control. The global controller outputs an actuation signal U_{ifo} to the suspension actuation and this signal is summed with the local actuation signal to give the total actuation signal to the suspension.

Under this configuration, if we treat X_{TM} as the output of interest, we can write its dependency to the two references input R_{ifo} and R_{TM}

$$X_{TM} = \frac{K_{sus}P_{sus}R_{TM} + K_{ifo}P_{sus}R_{ifo}}{1 + K_{sus}P_{sus} + K_{ifo}P_{ifo}P_{sus}}. \tag{1}$$

The stability criterion is that the characteristic equation $1 + K_{sus}P_{sus} + K_{ifo}P_{ifo}P_{sus}$ has no zeros in the right half of the complex plane and surely we can design K_{sus} and K_{ifo} to meet this requirement easily. However, this can be deceiving as we are dealing with coupled loops with different references.

Consider a scenario where both controllers are integrators, $K_{sus} \to K_{sus}/s$ and $K_{ifo} \to K_{ifo}/s$, and both plants are constants. Judging from stability margins, the loop transfer function has a constant -90° phase and therefore will be stable by definition regardless of the UGF. And, we can actual show this with final value theorem that the test mass position will converge at

$$\lim_{s\to 0} sX_{TM} = \lim_{s\to 0} \frac{K_{sus}P_{sus}R_{TM} + K_{ifo}P_{sus}R_{ifo}/s}{1 + K_{sus}P_{sus}/s + K_{ifo}P_{ifo}P_{sus}/s} = \frac{K_{ifo}P_{sus}R_{ifo}}{K_{sus}P_{sus} + K_{ifo}P_{ifo}P_{sus}}, \tag{2}$$

Note that the interferometer degrees of freedom X_{ifo} will not converge to the targeted position but will be somewhere close to it depending on the gains of the two controllers.

if we consider R_{ifo} as a step input, $R_{ifo} \to R_{ifo}/s$, which corresponds to closing the global loop with the local loop engaged beforehand. So, it appears that the system is seemingly stable without any problems. However, if we look at the process variables U_{sus} and U_{ifo} using the same theorem,

$$\begin{aligned} \lim_{s\to 0} sU_{sus} &= \lim_{s\to 0} s\left(K_{sus}/s\right)\left(R_{TM} - X_{TM}\right) \\ &= \lim_{s\to 0} \frac{K_{sus}}{s}\left(\frac{R_{TM}s + K_{ifo}P_{ifo}P_{sus}R_{TM} - K_{ifo}P_{sus}R_{ifo}/s}{1 + K_{sus}P_{sus}/s + K_{ifo}P_{ifo}P_{sus}/s}\right) \\ &= -\infty, \end{aligned} \tag{3}$$

$$\begin{aligned} \lim_{s\to 0} sU_{ifo} &= \lim_{s\to 0} s\left(K_{ifo}/s\right)\left(R_{ifo} - X_{TM}P_{ifo}\right) \\ &= \lim_{s\to 0} \frac{K_{ifo}}{s}\left(\frac{R_{ifo} + K_{sus}P_{sus}R_{ifo}/s - K_{sus}P_{sus}R_{TM}P_{ifo}}{1 + K_{sus}P_{sus}/s + K_{ifo}P_{ifo}P_{sus}/s}\right) \\ &= +\infty. \end{aligned} \tag{4}$$

So, as can be seen, although the summation of the two controller outputs gives a finite constant value to give a finite final test mass position, the manipulating varibles U_{sus} and U_{ifo} explodes which may or may not be an actual problem in reality which can make the system "unstable" even if the system is stable in the usual stability sense.

This particular scenario might not be an actual problem to the interferometer control because we don't usually use two integrators in this configuration. But, the purpose of the last example is to demonstrate that two controllers tend to nullify each others effect if they receive conflicting error signals, which is not uncommon and this is not exclusive to integrators and in fact may happen wherever the control bandwidth overlaps. This means that the efficacy of each controllers are both diminished.

Also, because we have to disengage conflicting local controllers (such as integrators), the take-over from local control to global control is not seamless. This means that if there system maybe susceptible to external disturbances during the take-over and it might take multiple trials for the take-over to be success so it might be time costly and can be potentially non-robust.

Another downside of this configuration is that if the global loop is suddenly opened for some reason, the sudden change in U_{ifo} will correspond to a kick to the suspension as it directly steps the overall actuation signal down to U_{sus} whereas the two signals used to complement each other to give good values of X_{TM}. This kick may or may not trivial, depending on the status of those controllers. But, if the kick happens to be large, the suspension will require a longer time to calm down which simply reduces the duty cycle of the detector.

2 Alternative Control Topology: Cascaded Control

To help mitigate some of the aforementioned adverse effects caused by the conventional control topology of interferometer control, we proposed an alternative control topology as shown in Fig. 2. In this configuration, the inner loop is the local control, whereas the outer loop represents the global interferometer control. Also, the global controller

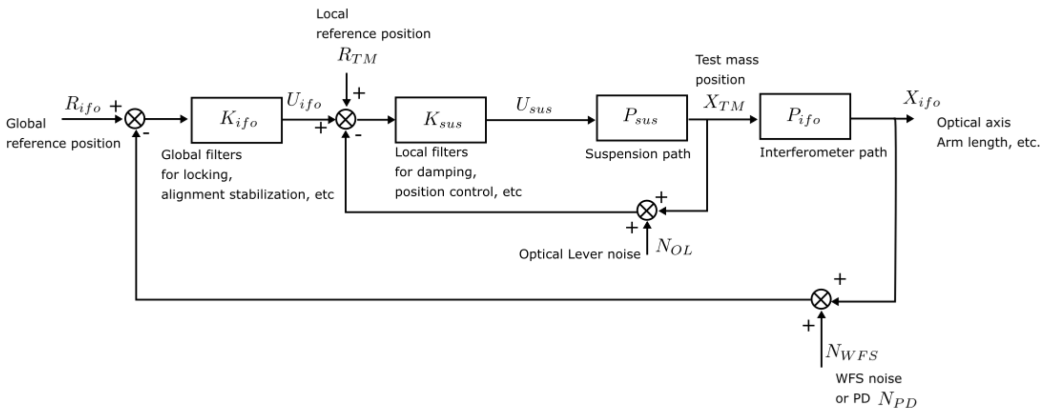

Figure 2: Cascaded control

output signal now connects to the "set point" of the local control, directly modifying the error signal of the local control loop. This way, the two controllers will not have conflicting effects because the outer loop will automatically correct the error signal of the inner loop. And, because the local control is not changed in this case, the local control works as usual for suppressing external disturbances that are introduced to the test mass displacement and will continue to work as long as the local loops are designed to be stable in the first place. Meanwhile, the outer loop makes sure that the interferometer degrees of freedom will reach the target reference regardless of the local reference. Moreover, because no local controller needs to be disengaged during the take-over, the process can be seamless, making that local control can be smoothly transferred to the global control. And, even if there is a sudden perturbation that disables the global loop, the sudden change in setpoint will not have as much adverse perturbation as the original configuration because the sudden change will be filtered by the local integrator so the test mass will slowly move back to the local reference.

In this configuration, the interferometer variable X_{ifo} reads

$$X_{ifo} = \frac{R_{ifo}K_{ifo}K_{sus}P_{sus}P_{ifo} + R_{TM}K_{sus}P_{sus}P_{ifo}}{1 + K_{sus}P_{sus} + K_{sus}P_{sus}K_{ifo}P_{ifo}}. \tag{5}$$

If we choose K_{sus} and K_{ifo} to be integrators, and the plants to be constants, the system will be stable regardless of the UGF since the loop transfer function has a phase between $-90°$ and $-180°$. Applying the final value theorem with the modifications $K_{sus} \to K_{sus}/s$, $K_{ifo} \to K_{ifo}/s$ (integrators) and $R_{ifo} \to R_{ifo}/s$ (step input), we get

$$\begin{aligned}\lim_{s\to 0} sX_{ifo} &= \lim_{s\to 0} \frac{R_{ifo}K_{ifo}K_{sus}P_{sus}P_{ifo}/s^2 + R_{TM}K_{sus}P_{sus}P_{ifo}}{1 + K_{sus}P_{sus}/s + K_{sus}P_{sus}K_{ifo}P_{ifo}/s^2} \\ &= R_{ifo},\end{aligned} \tag{6}$$

i.e., the interferometer can be controlled without the local control interfering. And, because the final value of X_{ifo} converges, it follows that all process/manipulated varibales converge as $X_{TM}P_{ifo} = X_{ifo}$, $U_{sus}P_{sus} = X_{TM}$ and $r_{ifo}(t = \infty) - x_{ifo}(t = \infty) = 0$.

The only limitation of this scheme is that $K_{sus}P_{sus}P_{ifo}$ must have non-zero gain (or rather, high enough gain) at frequencies where global control is required. Therefore, the ideal candidate of K_{sus} would be a broadband controller, whereas controller solely composes of multiple band-passes could be problematic for this scheme.

Originally, I thought the latter approach has better noise performance (therefore, I included sensing noise in the figures.). But, in second inspection and judging from the equations presented, they seemed to have similar noise behavior where the sensor noise dominates as the corresponding loop gain dominates. Nevertheless, this scheme provide the required tracking and robustness for alignment control and potentionally for length control. Both controllers harmonizes without conflict, and will not cause any aforementioned adverse effects which might appear with the current control topology.